# Agents for Active Network Management and Condition Monitoring in the Smart Grid

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## ABSTRACT

Recent interest in the smart grid or intelligent grid concept focuses on the desired capabilities of future energy networks, without much consideration of how to transition from current networks to the smart grid of tomorrow. This paper explores the required functionality and capability of an intelligent network management system, and shows how agent technology can address these needs. Agents can provide the platform for staged deployment of smart grid functionality, allowing the integration of current equipment and systems while remaining extensible for future developments. This paper describes how agent technology can be used to achieve this goal.

## Categories and Subject Descriptors

J.2 [**Computer Applications**]: Physical Sciences and Engineering—*Engineering*

## General Terms

Design, Standardization

## Keywords

agents, multi-agent systems, power engineering, smart grid

## 1. INTRODUCTION

Recently, there has been much interest in the idea of intelligent energy network and power systems technologies, with conferences and new journals dedicated to the smart grid concept [20, 13]. This concept generally includes a mixture of capabilities that can be grouped into three areas:

- Increased automation of current network functionality, such as voltage control and restoration;
- Wide scale deployment of functionality currently reserved for special cases, such as active network management and dynamic plant ratings;
- New functionality required for this complex automated system, such as self-managing and self-healing capabilities.

However, the industry faces the problem of how to transition from the networks of today to this smart grid future. Practically, some plan of staged deployment is required, allowing current technologies to link together to form a platform upon which more intelligent co-ordination can be built. This vision of a distributed collection of autonomous components working towards an efficiently operating network can be realized using agent technology, by exploiting various facets of the flexible autonomy each agent offers.

This paper considers the main requirements of the smart grid vision, and how the use of agent technology can ease the transition from current technology towards meeting the needs of the future.

## 2. SMART GRID REQUIREMENTS

Within the UK, a collaborative research project involving several UK universities, two distribution network operators (DNOs), and ABB investigated the design of an autonomous regional active network management system (AuRA-NMS). The scope of this project was to consider automating the decision making required for restoration, voltage control, power flow management, and network performance optimization, based on challenges arising from key areas of the DNOs' networks.

As a case study, this system perfectly highlights the transition from current networks to smarter systems, with more generic, network-agnostic solutions being applied to replace areas of functionality currently performed manually or with complex, bespoke systems[7]. As such, certain lessons and outcomes of the AuRA-NMS system apply more widely to the development and deployment of the smart grid vision, encompassing more functionality than simply control automation.

This project uncovered a set of industrial requirements for an intelligent network management system[7], summarized below.

- Safe and secure operation, meeting utilities' current standards.
- Flexibility, meaning the management system can reconfigure to accommodate changes in network, including topology, the connection of generation, protection settings, or plant ratings.
- Extensibility, allowing the addition of new management capabilities in the future to either replace existing functionality with better techniques or to enhance the overall mix of capabilities available.
- Failure tolerance and graceful degradation, ensuring safe and secure operation will not be compromised in the face of transient or permanent faults in communication networks, control hardware, system plant, or measurement instrumentation.

- Integration with existing equipment, including current protection and control systems, and the control centre distribution management system.

Multi-agent system technology is a platform that is capable of delivering these requirements. The power engineering community tends to use the Wooldridge definition of agency[15], stating that an intelligent agent displays flexible autonomy through a mixture of reactivity, pro-activeness, and social ability[21]. The autonomy of individual agents can be exploited to provide systems with an inherent fault tolerance, ensuring the failure of any one agent or communications link will not crash the entire system. Agent reactivity can be utilized to respond to reconfiguration of the network or new sources of generation, providing the flexibility required. New agents can be added to the system over time, and pro-activeness on the part of existing agents can include them in appropriate interactions, giving system extensibility. Finally, social ability and agents' messaging interfaces allow interaction with existing systems and equipment, often by wrapping the existing functionality within an agent.

The remaining sections of this paper consider how to exploit these capabilities of agent technology in order to deliver the smart grid vision.

## 3. CURRENT FUNCTIONALITY

As an initial step towards delivery of the full smart grid vision, network operations that are currently performed manually or by application-specific systems should be assessed for conversion to autonomous agents. These can be achieved by different routes: an agent-based system can be created to replace a manual process, and legacy systems can be wrapped as agents.

For some years now, agent-based systems for power engineering applications have been proposed. These applications, such as voltage control[1], microgrid management[10], distributed network control[19, 2], and restoration[18], can form the building-blocks of functionality needed as part of the smart grid. In order to take advantage of the benefits of agent technology for meeting the requirements of the smart grid, these individual agent systems must conform to standards for inter-agent communication, allowing information from, say, microgrid management to inform the restoration process.

While standards cover inter-platform communication, and messaging between agents down to the content level, the lack of a standard ontology will lead to problems integrating these application-specific multi-agent systems[16]. Three possible means of alleviating this problem have been suggested[4], of which the most feasible is the definition of an upper ontology for power systems applications[16]. Drawing upon existing data standards in the field, this upper ontology will form the common language for smart grid agents to discuss network state, possible control actions, and current capabilities.

However, a common situation when creating an industrial system is for the utility to have pre-existing software that performs certain tasks that should be encapsulated in the broader system. Rather than re-implementing this functionality, which has already undergone extensive robustness and accuracy testing in the field, the existing software can be wrapped as an agent for deployment alongside newer functionality. This route has been taken in cases such as post-fault analysis[8], where legacy expert systems for SCADA analysis and fault record interpretation were wrapped and deployed with agents for data collection and archival, to provide end-to-end data analysis.

By taking a mixture of legacy systems and application-specific groups of agents, and deploying them on open platforms with the social ability to meaningfully interact, this first wave of smart grid functionality can be realized. To draw a comparison with the World Wide Web, existing capabilities can be linked together with wrappers and data format translation, to produce SmartGrid 1.0. This provides a platform for further functionality to be deployed as it becomes available, paving the way for SmartGrid 2.0.

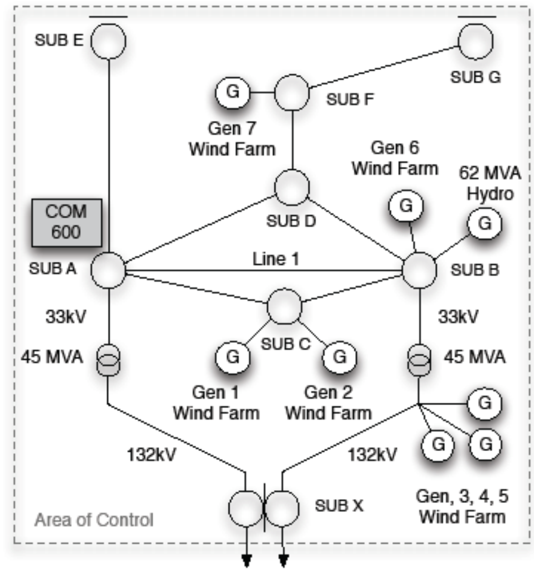


**Figure 1: Example network with distributed generation.**

## 4. FUTURE FUNCTIONALITY

While the wrapping of legacy systems as agents offers a route to speedy deployment, the flexibility of the system could be increased by re-examining the tasks that the legacy systems perform, with the aim of extracting generic reasoning tasks from bespoke functionality.

Figure 1 shows a case where under certain contingencies the network cannot support the connection of all the generation. The lower part of the diagram shows two 132kV lines each feeding one of two 45MVA transformers. Beyond these transformers the figure shows a 33kV section of network, with almost 85MW of installed generation (generators 1, 2, 6, 7, and 62MVA Hydro, all marked with a G). The minimum local load in this network is 10MW, meaning that if one of the two 45MVA transformers is removed from service while all generators are at full output, the remaining transformer would be overloaded.

The incremental connection of generators to this area of the network has led the utility to employ an increasing number of network automation schemes to handle different contingencies. Figure 2 shows one scheme for the above situation, where the loss of a transformer results in the switching

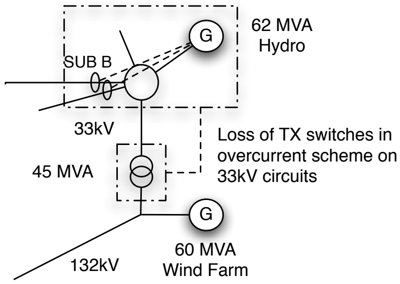


**Figure 2: One of nine network automation schemes.**

in of an overcurrent scheme at Sub B, which can disconnect the 62MVA Hydro generator if an overload is detected. This is one of nine such bespoke solutions currently in place for this network region.

But each of these schemes is fundamentally managing power flow to meet thermal constraints. A more generic solution would be to approach the problem of power flow management in a "network-agnostic" way, using techniques that can reason on an interchangeable model of the network rather than handling special cases. Then, as generation connects to the network the model can be updated, meaning that the solution will be extensible to future scenarios. Such generic approaches are being investigated; for example, power flow management can be cast as a constraint satisfaction problem[6]. However, this approach has no look-ahead capability, meaning that it may react to network conditions that do not necessarily require intervention (i.e. the boundary-hugging problem). Techniques that take cognizance of load and generation forecasts may offer advantages, and early results of the use of AI planning for setting voltage targets are promising[3].

This type of functionality could replace some of the agents foreseen for the first stage of smart grid deployment. Taking out the superseded agents and launching the replacements is trivial as long as good development practices are followed: any agents relying on the capabilities of the previous agents can locate the replacements through service advertisements registered with the directory facilitator. Similarly, high-level tasks such as power flow management are required on many areas of the network: launching duplicate power flow management agents each with their own specific network model is an elegant means of replicating this functionality for different regions.

It is anticipated that agents performing certain generic network tasks will be deployed alongside, and as replacements to, some of the legacy and application-specific systems described above, with the aim of providing enhanced automation and control capabilities for the network.

## 4.1 Condition Monitoring

One element of the smart grid vision is for condition monitoring to play a larger role in network operations. As such, the process of condition monitoring can be reconsidered to find generic solutions to on-line health assessment, mirroring the investigation of network-agnostic operational functionality described above. Design of such systems as agents will allow wide-area deployment of monitoring and asset health analysis, with the associated benefits of flexibility, extensibility, fault tolerance, and integration capabilities as discussed for operational functionality.

Through a case study of monitoring two particular transformers, the requirements of a generic architecture for plant monitoring were investigated[5]. These two 180MVA transformers are nearing the end of design life, but the owner utility believes life extension is possible with intensive online monitoring. As a result, a combination of fault diagnosis and detection of anomalous behavior was required, based on temperature, vibration, current, and dissolved gas data in addition to substation weather conditions.

Five high-level monitoring tasks were identified, which correspond to types of agent in the system:

- Data provision, where an agent provides access to sensors, databases, or other sources of data in the appropriate format for other agents;
- Service provision, where an agent performs data analysis or interpretation, such as fault diagnosis or anomaly detection;
- Data direction, linking data and service providers together in appropriate task flows;
- Archival, providing long term storage of data and information;
- External interfacing, allowing the connection of condition monitoring to external systems, user interfaces, and engineers.

Each condition monitoring task is performed by some mix of these types of agent. Specific examples implemented for the case study are fault diagnosis by dissolved gas analysis (DGA), fault diagnosis by partial discharge (PD) interpretation, and detection of unusual behavior through Conditional Anomaly Detection (CAD). The mixture of agents for each of these tasks is shown in Figure 3, where two data provider agents connect to a data warehouse and historical files; one external interface is used to provide a web-based engineer's user interface to the system; and the three monitoring tasks all require different mixes of service providers and data directors.

Of particular note, the partial discharge interpretation agents comprise a legacy agent-based system using a restricted ontology. Full rationale for the design of this system is given in [17], while the approach to integration with the wider system is explained in [5]. The anomaly detection capabilities and dissolved gas analysis are described in [5], along with results of on-line operation.

An agent-based condition monitoring system such as this can be deployed alongside network operational functionality within a smart grid system. This gives the immediate benefit of wider-scale and timely plant health assessment, and paves the way for further benefits, discussed further in Section 6.

# 5. EXTRA SYSTEM FUNCTIONALITY

The previous sections considered network functionality that is expected to become part of the smart grid. However, the smart grid system itself is a complex, decentralized system that will require a certain amount of management. As outlined above, the system will comprise a set of peer agents with potentially competing goals, and utilities will be rightfully wary of allowing a set of autonomous agents control over the network.

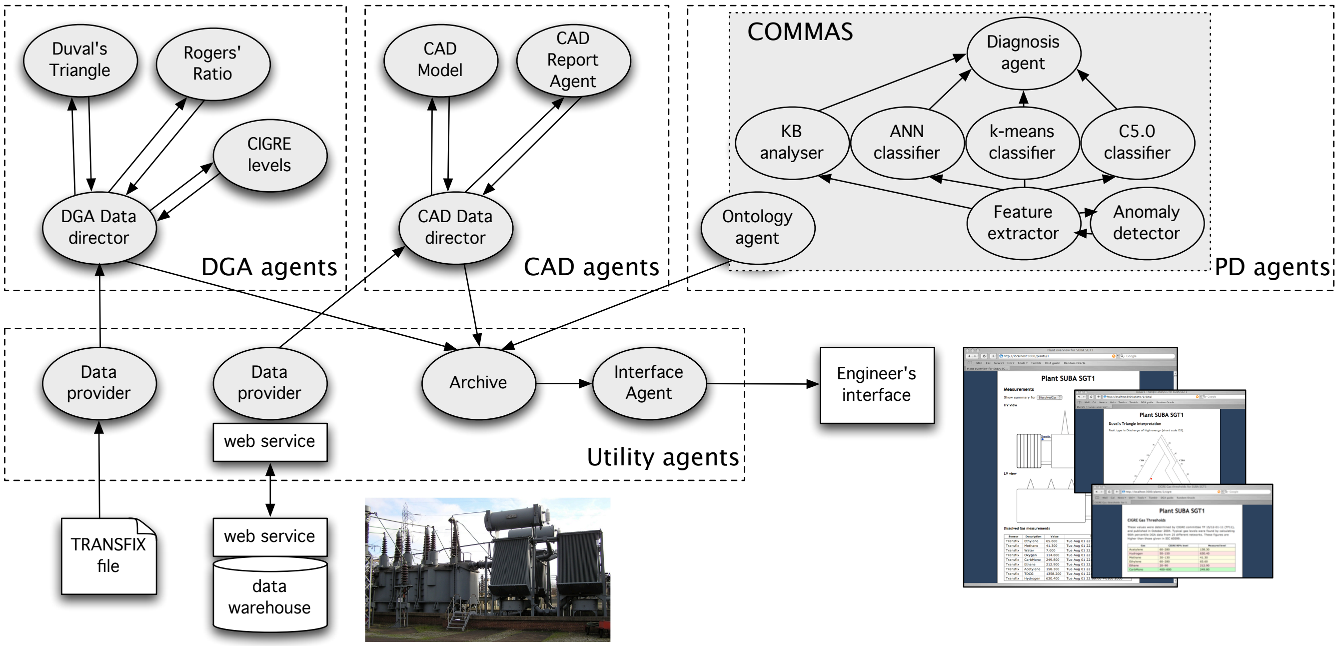


**Figure 3: On-line agent-based condition monitoring, with groups of agents split by high-level function.**

There are two broad approaches envisioned for managing this. First, certain agents can be created with explicit goals for ensuring safe and secure operation of the network. For example, an arbitration agent could be created to solve conflicts between operational plans, such as a situation where voltage control and power flow management agents produce plans for reconfiguration that conflict. Rather than allowing both to enact their plans concurrently, potentially resulting in unsafe network conditions, the arbitration agent is tasked with ensuring a plan to resolve one problem will not exceed limits elsewhere.

Another facet of safe and secure operation is to fairly allow access to computational resources for each agent. A software fault in one agent has the potential to take up processing time, memory, or long term storage space; starving other agents of those resources. Depending on the mix of agents physically co-located, this could result in a situation where the voltage control agent hangs, starving power flow management of resources, and neither task is adequately performed. Management agents can be created with the goal of ensuring appropriate use of resources. Specifically, any rogue agents could be suspended or terminated and restarted by these system management agents, providing the system with self-managing and self-healing capabilities.

The second approach to managing the smart grid system is to give utilities clear oversight on the behavior of each agent. It is very important for the control engineers to feel the system is functioning in a way that supports them in their role, rather than operating as a black box of unpredictable behavior[9]. Agents must be able to explain the reasons behind proposed plans of action, so that engineers can follow the rationale and gain confidence that the system is operating safely and securely. Secondly, engineers should be able to decide when and where the system will manage the network autonomously, and always have the option of reverting to manual control. Termed "selectively-devolved control", this idea means the engineer should be able to set the tasks and goals for agents in a given region as desired. Under particularly unusual outage conditions, for example, the engineer may want to manually manage thermal constraints while retaining automated voltage control and restoration. Practically, this could be achieved by suspending certain agents for the period of manual control.

In this way, the smart grid system as a whole can be managed through the deployment and suspension of agents with particular goals to ensure the smooth running of the system. Agents with oversight on the behavior of others can identify and resolve problems before they affect the security of the network, while engineers keep top-level control of the functionality of the system at any given time. The autonomous nature of agents is essential to achieving this flexible mixture of capability.

# 6. FUTURE BENEFITS

The availability of a platform of intelligent network operation capabilities and condition monitoring capabilities, such as those described above, provides opportunities for additional benefits to utilities. The co-location of these sets of functionality within the one smart grid system has the potential to improve both applications by the exchange of pertinent information.

As an example, consider the on-line monitoring of transformers and circuit breakers. This can currently be achieved by health assessment packages such as Kelman's TRANSFIX for transformers and Areva's CBWatch-2 for circuit breakers. Any information derived about plant health could be taken into consideration by an agent tasked with minimizing losses, for example, by altering the dynamic rating of a transformer to be more conservative, or inhibiting reconfiguration to avoid breaker operations, if the health of the asset is under suspicion.

Conversely, information about any control actions being taken could be useful to the condition monitoring system, by providing an explanation for transient changes in plant behavior. If a transformer is more heavily loaded than usual due to a fault elsewhere on the network, an increase in top oil temperature or a slight increase in gassing would be of less concern than such occurrences under normal conditions.

An agent-based system for condition monitoring would make this type of integration easier. As with control functionality, different types of condition monitoring and data analysis could be deployed as agents within the system, with the associated attributes of flexibility, extensibility, and robustness to failures. As described in Section 3, legacy condition monitoring systems can be wrapped as agents, and agent-based systems such as [14, 5] can integrate by conforming to communication standards defined for the smart grid system. In this way, condition monitoring becomes another building block of functionality for the intelligent grid, allowing utilities to derive maximum benefit from installed systems.

# 7. CHALLENGES FOR AGENT RESEARCH IN SMART GRIDS

This paper has outlined a roadmap towards the smart grid vision, using multi-agent systems technology as a platform for staged delivery of the requisite pieces. While there is some general agreement about the functionality that should exist in intelligent future networks, the path to that goal is largely unclear. By designing that functionality into intelligent agents, the required flexibility, extensibility, fault tolerance, and integration capabilities of the smart grid can be realized, ensuring safe and secure operation of the network.

However, the directions given here are predicated on certain areas of research coming to fruition. In particular, the community of researchers working in this area must agree on the following points:

- Standards for data exchange, including agent messaging standards and protocols and inter-platform communication;

- Creation of an upper ontology for smart grid terms and concepts, likely based on existing data standards such as the Common Information Model[12] and IEC 61850[11].

With this agreement in place, agents intended for intelligent network management will be capable of joining and participating in the open smart grid system architecture described above.

The IEEE Power and Energy Society (PES) Multi-Agent Systems Working Group is active in trying to address these issues. After publishing two papers on concepts and approaches[15] and tools and challenges[16] for the use of agents within power engineering, the Working Group is building a web site of resources and current practices for agent development. The Working Group offers a forum for information exchange and technical discussion between researchers in this field, allowing the most appropriate and useful standards to coalesce from the possibilities. In this way, the Working Group hopes to provide leadership for the development of smart grid agent systems.

# 8. CONCLUSION

This paper has considered the proposed functionality for future energy networks, and the corresponding requirements on an automated smart grid system. Agent technology can meet these requirements, delivering flexible, extensible, and fault tolerant communities of distributed intelligent components, providing capabilities such as active network management and condition monitoring. This possibility is largely dependent on community agreement on the standards employed for agent interaction, and the IEEE PES Multi-Agent System Working Group aims to offer guidance in this field.

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